On similarities of bulk observables in nuclear and particle collisions

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Abstract

We study the regularities in the multiparticle production data obtained from different types of collisions indicating the universality of the hadroproduction process. The similarities of such bulk variables like the charged particle mean multiplicity and the pseudorapidity density at midrapidity measured in nucleus-nucleus, (anti)proton-proton and e^+e^- interactions are analysed according to the dissipating energy of participants and their types. This approach shows a good agreement with the measurements in a wide range of nuclear collision energies from AGS to RHIC. The predictions up to the LHC energies are made and compared to experimental extrapolations.

1. Nucleus-nucleus collisions at RHIC probe matter at high densities and temperatures ever reached and provide us with an opportunity to investigate strong interactions up to extremely high energy density parton collisions. Of fundamental interest are bulk observables such as multiplicity and particle densities (spectra), which are sensitive tools for probing the dynamics of strong interactions. They give us information about the system formed in high energy collisions, both after cooling and hadronisation and as well during the formation and evolution of the collision initial state, and are thus powerful in distinguishing between different particle production models. Recent measurements at RHIC revealed striking evidences in the hadron production process including some universality between such basic observables as the mean multiplicity and the midrapidity density in complex ultra-relativistic nucleus-nucleus collisions *vs.* those measured in relatively "elementary" e^+e^- interactions. The values of these bulk observables are found to be similar for both types of reactions when measurements are normalised to pairs of participants ("wounded" nucleons [1] in heavy ion collisions) at the nucleon-nucleon center-of-mass (c.m.) energy, $\sqrt{s_{NN}}$, comparable to the c.m. energy $\sqrt{s_{ee}}$ of e^+e^- annihilation [2, 3]. This phenomenon is found to be independent of the energy spanning from $\sqrt{s_{NN}} = 19.6$ GeV to 200 GeV at RHIC. Assuming a universal mechanism of hadron production in both types of interactions which then depends only on the amount of energy transformed into particles produced, one would expect the same value of the observables to be obtained in hadron-hadron collisions at close c.m. energies. However, this is not the case: comparing measurements in hadronic data [4, 5] to the findings at RHIC, one obtains [2, 3, 6, 7, 8, 9, 10, 11, 12, 13, 14] quite lower values in hadron-hadron collisions. In the meantime, recent RHIC data from deuteron-gold interactions at $\sqrt{s_{NN}} = 200$ GeV unambiguously points to the same values of the mean multiplicity as measured in antiproton-proton collisions [3, 9, 14, 15, 16].

In this paper, we give a phenomenological interpretation of the above regularities obtained and compare these to the earlier data at lower energies. The particle production is considered to depend on the amount of the participant energy dissipated in collision. The comparison between different reactions is made on the basis of the type of participating patterns. This consideration introduces a tripling factor to be taken into account for the c.m. energy of a reaction and for appropriate treatment of participants to correctly compare the bulk variables from different reactions. Good agreement between the description proposed here and the experimental measurements is found.

2. In the consideration given here, the whole process of a collision is interpreted as the expansion and break-up into particles of an initial state, in which the whole available energy is assumed to be concentrated in a small Lorentz-contracted volume. There are no any restrictions due to the conservation of quantum numbers besides energy and momentum constraints allowing therefore to link the amount of energy deposited in the collision zone and features of bulk variables in different reactions. This approach resembles the Landau phenomenological hydrodynamical description of multiparticle production in relativistic particle collisions [17]. Though the hydrodynamical description does not match ideally the data on multiparticle production in the whole range of pseudorapidity, the model-based energy-scaling law of multiplicity gives good agreement with the measurements in such different reactions as nucleus-nucleus, pp, e^+e^- and νp collisions [18, 19]. Recently, the Landau model prediction for the longitudinal pion transport has been observed to be well within 5% ac-

curacy with the heavy-ion data [20]. This indicates that the main asserts of the Landau approach are useful to estimate fractions of the energy dissipated into particles produced in different reactions, particularly in nucleus-nucleus collisions [21].

As soon as the collision of two Lorentz-contracted particles leads to the full thermalisation of the system before extension, one can assume that the production of secondaries is defined by the fraction of energy of participants deposited in the volume of thermalized system at the collision moment. This implies that there is a difference between results of collisions of structureless particles like electron and positron and composite particles like proton, the latter considered to be built of constituents. Indeed, in composite particle collisions not all the constituents deposit their energy when they form a small Lorentz-contracted volume of thermalised initial state. As a result, the leading particles [22] formed out of those constituents which are not trapped in the interaction volume, carry away a part of energy effectively making it unavailable to participate in production of secondaries. From the other side, colliding structureless particles are ultimately stopped as a whole in the initial state of thermalized collision zone depositing their total energy in the small Lorentz-contracted volume. The latter makes this energy of the incoming particles wholly available for the production of secondaries.

A single nucleon represents a superposition of three constituent quarks. In this additive quark picture [23], most often only one quark from each nucleon contributes to the interaction, while other quarks are considered to be spectators. Thus the initial thermalized state which is responsible for the number of produced secondary particles is pumped in only by the energy of the interacting single quark pair. The quark spectators form hadrons being not stopped in the thermalized volume at the collision moment do not participate in secondary particle production. The later means that only $1/3$ of the entire nucleon energy is available for particle production. In e^+e^- annihilation, the incident particles are structureless and therefore, the total interaction energy is deposited in the thermalized collision zone. From this and the above consideration, one expects that the resulting bulk variables like the multiplicity and rapidity distributions should show identical features in proton-proton collisions at the c.m. energy $\sqrt{s_{\mathrm{pp}}}$ and e^+e^- interactions at the c.m. energy $\sqrt{s_{\mathrm{ee}}} \simeq \sqrt{s_{\mathrm{pp}}}/3$. Note that for the mean multiplicity, similar behaviour was obtained experimentally in the beginning of LEP activity [24].

In heavy ion collisions, more than one quark per nucleon interacts due to the large size of nucleus and the long path of interactions inside the nucleus. The more central the nucleus-nucleus collision is, the more interactions occur and the larger energy amount is spent for secondary particle production. In central nuclear collisions, a contribution of constituent quarks rather than participating nucleons seem to determine the properties of produced particle distributions [25]. In the most central collisions, the density of matter is so high (almost saturated) that all three constituent quarks from each nucleon may participate nearly simultaneously in collision depositing their energy coherently into thermalized collision zone. The total entire energy of nucleons included in the most central fraction of colliding nuclei is available for secondary particle production. Recalling that in proton-proton collisions, where only one out of three constituent quarks from each proton interacts, one expects the features of the bulk variables per pair of participants measured in the most central heavy-ion interactions at the c.m. energy $\sqrt{s_{\mathrm{NN}}}$ to be similar to those from proton-proton collisions at three times larger c.m. energy, $\sqrt{s_{\mathrm{pp}}} \simeq 3\sqrt{s_{\mathrm{NN}}}$. This makes the most central collisions of

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nuclei akin to e^+e^- collisions at the same c.m. energy from the point of view of the resulting bulk variables.

3. Applying the above consideration, we compare in Fig. 1, in the $\sqrt{s_{\mathrm{NN}}}$ energy range from a few GeV to 200 GeV, the c.m. energy dependence of the mean multiplicity as measured in nucleus-nucleus $[2, 3, 26, 27, 28, 29]$, and e^+e^- interactions $[36, 37, 38, 39, 40, 41, 42, 43, 44]$ *vs.* that but at the three times larger c.m. energy in (anti)proton-proton pp/$\bar{\mathrm{p}}$p collisions $[30,31,32,33,34]$. The multiplicity values in nuclear collisions are given divided by the number of participant pairs and the energy value gives the c.m. energy per nucleon, $\sqrt{s_{\mathrm{NN}}}$. For the data on e^+e^- annihilation at energies above the Z^0 peak, we give the multiplicity values averaged[1] here from those recently published by LEP experiments at LEP1.5 $\sqrt{s_{\mathrm{ee}}} = 130$ GeV $[36, 37]$ and LEP2 $\sqrt{s_{\mathrm{ee}}} = 200$ GeV $[37, 38]$ energies: $23.35 \pm 0.20 \pm 0.10$ (LEP1.5) and $27.62 \pm 0.11 \pm 0.16$ (LEP2). Figure shows also the average multiplicity fit to pp/$\bar{\mathrm{p}}$p data obtained in $[30]$ and the ALEPH fit $[37]$, based on the 3NLO perturbative QCD calculations $[48]$, to e^+e^- data.

First, one can see from Fig. 1 that the pp/$\bar{\mathrm{p}}$p data are very close to the data from e^+e^- annihilation measured at the c.m energy $\sqrt{s_{\mathrm{ee}}} = \sqrt{s_{\mathrm{pp}}}/3$. This nearness, as the fits confirm spanning from GeV to TeV c.m. energies, decreases the already small deficit in the e^+e^- data compared to the pp/$\bar{\mathrm{p}}$p data as the energy increases. Note that at TeV energies this deviation is almost five-six times smaller the area covered by the fit errors. The deviation can be attributed to the inelasticity factor, or leading particle effect $[22]$ in pp/$\bar{\mathrm{p}}$p collisions, which is known to decrease with the c.m. energy. Then, at lower c.m. energies, some fraction of the energy of spectators contributes more into the formation of the initial state, while the spectators passed by. This leads to the excess of the average multiplicity in pp/$\bar{\mathrm{p}}$p collisions compared to that in e^+e^- interactions at $\sqrt{s_{\mathrm{ee}}} = \sqrt{s_{\mathrm{pp}}}/3$ as it is observed from Fig. 1.

Comparing further the average multiplicity values from pp/$\bar{\mathrm{p}}$p collisions to those from heavy-ion reactions, one finds that the data points are amazingly close to each other when the heavy-ion data is confronted with the hadronic data at the energy $\sqrt{s_{\mathrm{pp}}} = 3\sqrt{s_{\mathrm{NN}}}$ and, according to the just made observation, to the e^+e^- data at the same energy as the nucleus-nucleus reaction data are taken. All these findings agree well with our interpretation of the multihadron production process and the consequences the bulk variables to be similar in the reactions considered when measured at $\sqrt{s_{\mathrm{NN}}}$ and $\sqrt{s_{\mathrm{ee}}}$ being about a third of $\sqrt{s_{\mathrm{pp}}}$. The inclusion of the tripling energy factor indeed allows *energy-independent* description of such a fundamental variable as the mean multiplicity in *simultaneously* e^+e^-, pp/$\bar{\mathrm{p}}$p and central nucleus-nucleus collisions. This shows that the particle production process in headon nucleus-nucleus collisions is derived by the energy deposited in the Lorentz-contracted volume by a single pair of effectively structureless nucleons similar to that in e^+e^- annihilation and of quark pair interaction in pp/$\bar{\mathrm{p}}$p collisions. To note is that an examination of Fig. 1 reveals that there is no need to rescale the $\sqrt{s_{\mathrm{ee}}}$ by a factor of 1/2 to match the $\bar{\mathrm{p}}$p data as earlier was assumed $[2, 8, 9]$, while recognised $[3]$ to unreasonably shift the e^+e^- data[2] on the pseudorapidity density at midrapidity when compared to the heavy-ion measurements.

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[1]The averaging procedure is adopted from the PDG review $[46]$ for the averaging over N measurements. The errors are multiplyed by the S-factor, where $S = \sqrt{\chi^2/(N-1)} > 1$ or $S = 1$ otherwise.

[2]Recall that the factor 1/3 but not 1/2 was already found earlier in $[24]$ to give an appropriate rescaling of the pp mean multiplicity data relative to those from e^+e^- annihilation.

This discrepancy, as shown, finds its explanation in our consideration, within which the data on *both* the mean multiplicity and the midrapidity density (*vide infra*) are self-consistently matched for different reactions.

Fig. 1 shows that the mean multiplicities measured in different types of interactions are close to each other starting from the SPS $\sqrt{s_{\mathrm{NN}}}$ energies, and become particularly close at $\sqrt{s_{\mathrm{NN}}} \gtrsim 50$ GeV. At lower energies, however, small deviation in the measurements is visible. The nucleus-nucleus data points are slightly below the measurements from e^+e^- and hadronic experiments. At $\sqrt{s_{\mathrm{NN}}} \lesssim 10$ GeV, the nuclear data departure increases further, and the data start to decrease faster with the energy decreasing than the measurements from pp and e^+e^- experiments do. On the other hand, as c.m. energy increases above a few tens GeV, the heavy-ion data start to exceed the e^+e^- data and reaches the mean multiplicity values from $\bar{\mathrm{p}}$p interactions. From this, one concludes on the two different regions of the rise of the mean multiplicity nuclear data with the energy increase: one being steeper at $\sqrt{s_{\mathrm{NN}}}$ of a few tens GeV, and another one slower at lower energies down to a few GeV. One also can see that the multiplicities in nuclear reactions increase faster with the c.m. energy than this can be found in other interactions, while the effect is relatively small keeping the data points close to each other at fixed c.m. energy $\sqrt{s_{\mathrm{NN}}}$ and $\sqrt{s_{\mathrm{ee}}}$ of the value of $\sqrt{s_{\mathrm{pp}}}/3$.

The observations made can be understood in terms of the overlap zone. At relatively low energies, the initial thermalized state, formed in headon nuclear collisions, are most likely to occur in the overlap zone of colliding nuclei along the incident direction, so the nucleons at the periphery are not contributing. Since the energy of the collision is small and, therefore, is almost entirely and fast converted into particles produced, the rest parts of the nuclei start to fragment into pieces by expanding overlap zone. The smaller the energy is, the less particles will be produced in a collision. At low energies, due to our approach, the mean multiplicity in pp collisions at $\sqrt{s_{\mathrm{pp}}}$ is expected to be larger than in nucleus-nucleus collision at $\sqrt{s_{\mathrm{NN}}} = \sqrt{s_{\mathrm{pp}}}/3$. As the $\sqrt{s_{\mathrm{NN}}}$ increases, the mean multiplicity in nucleus-nucleus collisions is supposed to increase faster than that in pp/$\bar{\mathrm{p}}$p interactions at $\sqrt{s_{\mathrm{pp}}} = 3\sqrt{s_{\mathrm{NN}}}$. Indeed, in pp/$\bar{\mathrm{p}}$p collision we consider a single pair of constituent quarks to form participants, while in nuclear collisions, the effectively structureless protons entirely participate. So, at the same energy per participant, at low energies, in (anti)proton collisions, all the energy of a pair of interacting constituent quarks is converted into particles produced, while in nuclear collision some fraction of energy is used to break-up nuclei by expansion of the small overlap zone. As the energy increases, the nature of the rise in (anti)proton collisions should not change significantly since (anti)protons are considered interacting the same way as at lower energies, *i.e. via* a pair of constituent quarks depositing their energy into secondaries. In contrary, in (central) nuclear collisions, the Lorentz contraction starts to play a significant role involving more nucleons into overlap zone. Due to this, more energy becomes available for particle production which makes the mean multiplicity rise faster than at lower energies. To add is that this effect attracts currently special consideration in different approaches [49].

Note that the total multiplicity is not very sensitive to the above, and this is seen in Fig. 1, where, as we already mentioned, the difference between hadronic and nuclear data is small, once tripling energy factor is taken into account. On the other hand, due to fact that differences are related mostly to the interaction zone and consequently, to the central rapidity region, one would expect the differences to be more pronounced in the midrapidity comparison, as we indeed find below.

4. In Fig. 2, we compare the values of the pseudorapidity densities per participant pair at midrapidity as a function of c.m. energy, from most central nucleus-nucleus collisions at RHIC [6,10,27,50,51], CERN SPS [52,53,54,55], and AGS [56] *vs.* those measured in pp/$\bar{\text{p}}$p interactions at CERN [4,30,57,32] and Fermilab [5,34,59]. The comparison is given the same way as the mean multiplicity is shown in Fig. 1, *i.e.* the data from nucleus-nucleus collisions are plotted at the energy $\sqrt{s_{\text{NN}}} = \sqrt{s_{\text{pp}}}/3$. One can again see that up to the existing $\sqrt{s_{\text{NN}}}$, the data from hadronic and nuclear experiments are close to each other being consistent with our interpretation. The measurements from the two types of collisions coincide at $8 \text{ GeV} < \sqrt{s_{\text{NN}}} < 20 \text{ GeV}$ and are of the magnitude of the spread of heavy-ion data points at the highest energy of 200 GeV. For a few GeV energy shown, one can also see the visible difference. The data shown in Fig. 2 indicates that the deviation between the two types of collisions increases with the c.m. energy due to faster increase of the midrapidity density values obtained in heavy-ion collisions in comparison with those measured in $\bar{\text{p}}$p interactions. At lower energies too, the nuclear data, being lower than the pp data, increases faster. The latter means that, as we discussed above, in contrast to the mean multiplicity, which is in general defined by the total yield of the reaction, so being less sensitive to reaction details, the midrapidity density depends on some additional factor. As the midrapidity density is measured in the very central region, where the participants longitudinal velocities are zeroed, it is natural to assume that this factor is related to the size of the Lorentz-contracted volume of the initial thermalized system determined by participating patterns.

To take into account the corresponding correction, let us consider our picture in the framework of the Landau model which reasonably well describes the bulk variables measured and is, by its nature, near to our interpretation as discussed above. Using this model, one finds for the ratio of the charged particle rapidity density $\rho(y) = (2/N_{\text{part}})dN_{\text{ch}}/dy$ per participant pair at the midrapidity value $y = 0$ in heavy-ion reaction, ρ_{NN}, to the density ρ_{pp} in pp/$\bar{\text{p}}$p interaction,

$$\frac{\rho_{\text{NN}}(0)}{\rho_{\text{pp}}(0)} = \frac{2\,N_{\text{ch}}}{N_{\text{part}}\,N_{\text{ch}}^{\text{pp}}}\sqrt{\frac{L_{\text{pp}}}{L_{\text{NN}}}}\,. \tag{1}$$

Here, N_{part} is the number of participants in heavy-ion collision, N_{ch} ($N_{\text{ch}}^{\text{pp}}$) is the multiplicity in nucleus-nucleus (pp/$\bar{\text{p}}$p) collision and $L = \ln\frac{\sqrt{s}}{2m}$, where m is the mass of a participating pattern, *e.g.* of a proton, m_{p}, in central heavy-ion collisions. According to our interpretation, we compare in the ratio (1) the rapidity density $\rho_{\text{NN}}(0)$ at $\sqrt{s_{\text{NN}}}$ to the rapidity density $\rho_{\text{pp}}(0)$ at $\sqrt{s_{\text{pp}}}/3$. Due to the above, we consider a constituent quark of mass $\frac{1}{3}m_{\text{p}}$ as a participating pattern in pp/$\bar{\text{p}}$p collisions, and a proton as an effectively structureless participant in most central nucleus-nucleus collisions. Then, from Eq. (1) one obtains:

$$\rho_{\text{NN}}(0) = \rho_{\text{pp}}(0)\frac{2\,N_{\text{ch}}}{N_{\text{part}}\,N_{\text{ch}}^{\text{pp}}}\sqrt{1 - \frac{4\ln 3}{\ln\left(4m_{\text{p}}^2/s_{\text{NN}}\right)}}\,. \tag{2}$$

Using the fact that the transformation factor from rapidity to pseudorapidity does not influence the above ratio and substituting the data values of N_{ch} and $N_{\text{ch}}^{\text{pp}}$ shown in Fig. 1 and of $\rho_{\text{pp}}(0)$ shown in Fig. 2, one obtains from Eq. (2) the values of pseudorapidity density in nucleus-nucleus collisions. These values are displayed in Fig. 2 by solid line. One can see that

the correction made provides a good agreement between the calculated $\rho_{\mathrm{NN}}(0)$ values and the data. This justifies the above argued midrapidity multiplicity dependence on participant type determining the volume of the initially thermalized system. Eq. (2) shows also the importance of the correction, in particular in case of the Landau model, for the participant type to be introduced to properly estimate the midrapidity density. This correction is in agreement with our description where the proper participants have to be considered for the corresponding reaction. To note is that the pseudorapidity density at midrapidity in $\mathrm{e}^+\mathrm{e}^-$ annihilation is shown [3] to coincide with that from nucleus-nucleus data in the wide energy range and is in agreement with our assumptions and the above expectations.

As we discuss above for the mean multiplicity, one can see that the pseudorapidity density at midrapidity is indeed more sensitive to the differences in the multiparticle production process at lower and higher energies. The increase of the density measured in nuclear collisions at $\sqrt{s_{\mathrm{NN}}}$ less than the highest SPS energy is steeper than it is above it. This is also true for $\mathrm{pp}/\bar{\mathrm{p}}\mathrm{p}$ data which is fitted with different log functions: with the single log fit at lower $\sqrt{s_{\mathrm{pp}}}$ [4] and with 2nd order log polynomial at higher energies [5]. It is worth noting how well our consideration of tripling energy and properly treating the type of participants – quarks in $\mathrm{pp}/\bar{\mathrm{p}}\mathrm{p}$ and protons in nuclear collisions – takes into account the different energy behaviour in $\mathrm{pp}/\bar{\mathrm{p}}\mathrm{p}$ collisions from which the nuclear data can be deduced. Note that the same two regions we find here studying the pseudorapidity density at midrapidity $\rho_{\mathrm{NN}}(0)$, recently has been reported in [10,11] by PHENIX, when analysing the ratio of the transverse energy density to the pseudorapidity density at midrapidity as function of energy. From this finding, one can expect to obtain similarities in the transverse energy density in $\mathrm{pp}/\bar{\mathrm{p}}\mathrm{p}$ *vs.* that in headon heavy-ion collisions in the frame of our description. The transition region at the SPS energies has been found also by NA49 [28], which can be treated within our approach too, without any additional assumptions.

From the above, we conclude that the description proposed here allows explaining the similarity obtained between the bulk variables measured in central heavy ion collisions compared to other types of reactions. Namely, we consider the constituent quark structure as a frame governing the formation of the initial thermalized state in the collision zone. Then a pair of structureless participating patterns being stopped in a Lorentz-contracted volume is the main source of energy dissipating into particles produced. This makes only a fraction of the total energy of colliding composite object like (anti)proton available for formation of secondary particles. In contrary, in headon collision of nuclei, nucleons are considered as being structureless, similar to $\mathrm{e}^+\mathrm{e}^-$ annihilation, owing to almost coherent deposition of energy by all participating constituent quarks. This provides the total energy per nucleon being available for the formation of the thermalized Lorentz-contracted volume and consequently, for the secondary particle production. Therefore, in headon nuclear collisions, and in $\mathrm{e}^+\mathrm{e}^-$ annihilation as well, a tripling factor is needed to be taken into account for energy and mass of interacting patterns to adjust the global variables to those in $\mathrm{pp}/\bar{\mathrm{p}}\mathrm{p}$ collisions. It is worth noting that recently, the constituent quark picture has been exploited to reasonably model the heavy-ion pseudorapidity and transverse energy data [58].

5. An intriguing issue, which can be considered from the interpretation given here in tracing similarities of the bulk observables in nucleus-nucleus collisions and in "simpler" reactions, particularly in such like nucleon-nucleon ones, is to make some predictions for the

bulk variables in asymmetric nucleon-nucleus collisions. In the frame of our consideration, in these interactions, the mean multiplicity value per pair of participant measured at some $\sqrt{s_{\mathrm{NN}}}$ is expected to have the same value as that is in pp/$\bar{\mathrm{p}}$p collisions at the same $\sqrt{s_{\mathrm{pp}}}$ as $\sqrt{s_{\mathrm{NN}}}$. Indeed, assuming an incident proton in p-nucleus collisions interacts in a way it would interact in pp collision, the secondary particles in the reaction are considered to be created out of energy deposited by interaction of a single pair of constituent quarks, one of which is from the proton and another one from a nucleon of the interacting nucleus. So, in fact, only this pair of constituent quarks converts their energy into secondary particles similar to that in pp/$\bar{\mathrm{p}}$p interactions. This also implies that the mean multiplicity being defined mostly by the energy deposited by participants – by the pair of constituent quarks – is not expected to depend on the centrality of nucleus-induced collisions, *i.e.* on the number N_{part} of participants (within uncertainties due to intranuclear effects, *e.g.* Fermi motion). These expectations are recently shown to be well confirmed in the RHIC data on deuteron-gold interactions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV [3, 15, 16]. Moreover, the effect of the similarity obtained at RHIC is shown [3, 15, 16] to be true for hadron-nucleus collisions at $\sqrt{s_{\mathrm{NN}}} \approx 10$–20 GeV too. The same seems to be correct also for the pseudorapidity density at midrapidity, which is already supported to be a trend [3,16]. This can also explain the necessity of the multiplication [60] of the pp/$\bar{\mathrm{p}}$p pseudorapidity distribution by a number of the Au participants to correct the QCD saturation model predictions [61] to fit the data gold nucleus region of the pseudorapidity distribution from dAu interactions.

6. As it is found, see Fig. 2, the pseudorapidity density at midrapidity shows increase in the difference between the values obtained from central nucleus-nucleus collisions and those from pp/$\bar{\mathrm{p}}$p interactions as the c.m. energy of reactions increases above the highest SPS energy. As shown above, this difference is connected with a size of the Lorentz-contracted volume. At the c.m. energies available today in nucleus-nucleus experiments, this difference is comparable with the difference in the measurements. It is of interest to know the density values for higher than the experimentally reached $\sqrt{s_{\mathrm{NN}}}$ in order to check whether the deviation between the pp/$\bar{\mathrm{p}}$p and nucleus-nucleus midrapidity densities becomes more pronounced as it is expected. Unfortunately, no measurements, except the midrapidity density for pp/$\bar{\mathrm{p}}$p data, are available for the variables in Eq. (2) beyond $\sqrt{s_{\mathrm{NN}}} = 200$ GeV. The densities for $\bar{\mathrm{p}}$p interactions are measured up to $\sqrt{s_{\mathrm{pp}}} = 1.8$ TeV, and these high-energy $\bar{\mathrm{p}}$p data can be compared to at least some estimates for the midrapidity density in nucleus-nucleus collisions at $\sqrt{s_{\mathrm{NN}}} = \sqrt{s_{\mathrm{pp}}}/3$. To this end, we extrapolated the values calculated from Eq. (2) utilizing the function analogous to that found [5] to fit well the $\bar{\mathrm{p}}$p data. Both the prediction for nucleus-nucleus collisions and the fit for $\bar{\mathrm{p}}$p data are shown in Fig. 2.

The dependence of the midrapidity density on the c.m. energy in nucleus-nucleus interactions, which we show by the dashed line in Fig. 2, agrees well with the calculations we made above based on Eq. (2) shown by solid line. This dependence indicates that the midrapidity density in heavy ions increases faster with the c.m. energy than that in pp/$\bar{\mathrm{p}}$p collisions considered at the three times larger c.m. energy $\sqrt{s_{\mathrm{pp}}}$. As we predict within our consideration and show in Fig. 2 in an assumption that the same behaviour as at the SPS–RHIC energies extends up to the LHC energies, the density $\rho_{\mathrm{NN}}(0)$ is found to be ~ 7.7 at the c.m. energy $\sqrt{s_{\mathrm{NN}}} = 5.5$ TeV of heavy-ion collisions at LHC. From the CDF fit [5] and assuming it covers LHC energies, one obtains the value of ~ 6.1 for the pseudorapidity

density at midrapidity expected for pp interactions at LHC at $\sqrt{s_{\mathrm{pp}}} = 14$ TeV. The value we obtain for $\rho_{\mathrm{NN}}(0)$ at LHC energy is consistent with that of ~ 6.1 given in the PHENIX extrapolation [10, 11] within 1-2 particle error acceptable in the calculations we made. Our result is in a good agreement with the recent ATLAS Monte Carlo tuned values [62]. Taking into account that the LHC $\sqrt{s_{\mathrm{NN}}}$ is close enough to $\sqrt{s_{\mathrm{pp}}}/3$, the nearness of the values, predicted for the LHC by us and estimated independently and based on the experimental fit in the wide range of energies by PHENIX [10, 11], demonstrates that our interpretation provides an experimentally grounded description and predictive ability. It is interesting to note that as the energy changes significantly the particle production process seems not to change from that above highest SPS nuclear collision energies, in contrast to what happens when the $\sqrt{s_{\mathrm{NN}}}$ departs to the SPS energies from lower $\sqrt{s_{\mathrm{NN}}}$ as discussed.

As soon as we describe nucleus-nucleus midrapidity density using pp/p̄p data in wide energy range spanning form a few GeV to hundreds GeV, now we can solve Eq. (2) for the mean multiplicity $N_{\mathrm{ch}}/(0.5N_{\mathrm{part}})$ to describe the nuclear data where no measurements exist and to predict the mean multiplicity energy dependence at higher energies. In this calculations, we use the fits of $\rho_{\mathrm{pp}}(0)$ [5] and $N_{\mathrm{ch}}^{\mathrm{pp}}$ [4] and approximation for $\rho_{\mathrm{NN}}(0)$ as functions of the c.m. energy shown in Figs. 1 and 2. From the resulted curve for $N_{\mathrm{ch}}/(0.5N_{\mathrm{part}})$ as a function of $\sqrt{s_{\mathrm{NN}}}$ plotted in Fig. 1, one finds that the heavy-ion mean multiplicity per participant pair at $\sqrt{s_{\mathrm{NN}}} = 5.5$ TeV is just about 10% above the $N_{\mathrm{ch}}^{\mathrm{pp}}(\sqrt{s_{\mathrm{pp}}})$ approximation at $\sqrt{s_{\mathrm{pp}}} = 14$ TeV and about 3.3 times larger the data mean multiplicity from heavy-ion collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV. Again, this number is comparable with the estimate made from the pseudorapidity density spectra by PHENIX [10, 11] and points out to no evidence for change of behaviour in the energy dependence as the $\sqrt{s_{\mathrm{NN}}}$ increases by about two magnitudes from the top SPS energy. Nevertheless, one can see that the data obtained at the highest RHIC energy give a hint to some border-like behaviour of the mean multiplicity where the pp/p̄p data saturate the nuclear data, and another region of the rise is possible to be found (as at low energies). This makes heavy-ion experiments at $\sqrt{s_{\mathrm{NN}}} > 200$ GeV of particular interest.

Given the importance of the multiplicity and produced particle spectra as control observables of the particle production process, various theoretical descriptions have been proposed and confronted to the nucleus-nucleus collision data, in particular to the mean multiplicity and the midrapidity density measurements [3, 12, 13, 63], the bulk variables considered here. Most of the models are shown to reproduce reasonably at least some part of the measurements or the trend obtained in the data, while they are found to be less successful in describing all the experimental findings. Despite many questions are still open and there are significant challenges for theory, the message of inability to reproduce the measurements taken at highest RHIC energies by scenarios solely based on interactions between hadronic objects is clearly given. The system produced at highest density and temperature ever reached experimentally requires a partonic approach to be explored for its description. In this sense, our interpretation invokes partonic picture being the necessary ingredient as the description utilizes the constituent quark framework.

7. In summary, we analyse the similarities of the bulk observables obtained in heavy-ion reactions, (anti)proton-proton and e^+e^- interactions in the large c.m. energy interval from a few GeV to hundreds GeV. The similarities of such bulk observables like the mean mul-

tiplicity and pseudorapidity density at midrapidity are compared to our expectations under assumption of the universality of a mechanism of the multiparticle production in different types of interactions. Within the description proposed, secondary particles are produced according to the amount of energy deposited by participants and depending on their type. The bulk observables in headon nuclear collisions are treated on the base of interactions of nucleons, considered as effectively structureless patterns wholly depositing their energy, similar to that in e$^+$e$^-$ annihilation. It is shown that the observables obtained from nucleon-nucleon collisions are similar to those from nuclear or e$^+$e$^-$ interactions when one considers the single constituent quark pair interaction picture for nucleon-nucleon collisions at the c.m. energy three times larger the energy of nuclear or e$^+$e$^-$ collisions. The correction to take into account the tripling factor in the c.m. energy and for proper treatment of participating patterns is found to explain the actual measurements. Two separated regions in the measurements with a boundary about highest SPS nuclear experiment energy are reproduced. The approach is extended to and the consequences are made for particle-nucleus collisions showing agreement with recent RHIC data. The predictions for higher LHC energies within the proposed interpretation are made, found to follow the experimentally obtained extrapolations. As shown, experiments at RHIC, given a remarkable opportunity to expand investigations to the highest so far achieved density of matter, allow to reveal signatures of new phenomena and provide indispensable knowledge on the dynamics of strong interactions. This makes of great interest further comprehensive analyses of the data obtained up to RHIC energies and to be obtained at the higher energies challenging to the better understanding of the discoveries made and testing the predictions.

Acknowledgements

References

[1] A. Białas, B. Bleszyński, W. Czyż, Nucl. Phys. B **111** (1976) 461; A. Białas, W. Czyż, Acta Phys. Pol. B **36** (2005) 905.

[2] PHOBOS Collaboration, B.B. Back *et al.*, nucl-ex/0301017.

[3] PHOBOS Collaboration, B.B. Back *et al.*, nucl-ex/0410022, and at `http://www.phobos.bnl.gov/`, and refs. therein.

[4] UA5 Collaboration, G.J. Alner *et al.*, Z. Phys. C **33** (1986) 1.

[5] CDF Collaboration, F. Abe *et al.*, Phys. Rev. D **41** (1990) 2330.

[6] PHOBOS Collaboration, B.B. Back *et al.*, Phys. Rev. Lett. **85** (2000) 3100.

[7] PHENIX Collaboration, K. Adcox *et al.*, Phys. Rev. Lett. **86** (2001) 3500; PHOBOS Collaboration, B.B. Back *et al.*, Phys. Rev. Lett. **87** (2001) 102303; **88** (2002) 022302. Phys. Rev. C **65** (2002) 061901.

[8] P. Steinberg, Proc. XXII Int. Physics in Collision Conf. (Stanford, USA, 2002), Eds. D. Su, P. Burchat (SLAC-R-607, 2002), p. 168, eConf C020620 (2002) FRBT03; Proc. XXVII Int. Conf. on Ultra Relativistic Nucleus-Nucleus Collisions: Quark Matter 2004 (Oakland, USA, 2004), Eds. H.G. Ritter, X.-N. Wang, J. Phys. G **30** (2004) S683.

[9] W. Busza, Proc. XLIV Cracow School of Theoretical Physics (Zakopane, Poland, 2004), Acta Phys. Pol. B **35** (2004) 2873.

[10] PHENIX Collaboration, S.S. Adler *et al.*, Phys. Rev. C **71** (2005) 034908.

[11] A. Milov (for the PHENIX Collaboration), talk at Int. Workshop on Particle Multiplicity in Relativistic Heavy Ion Collisions: Focus on Multiplicity (Bari, Italy, 2004), nucl-ex/0409023.

[12] PHENIX Collaboration, K. Adcox *et al.*, nucl-ex/0410003, and refs. therein.

[13] BRAHMS Collaboration, I. Arsene *et al.*, nucl-ex/0410020, and refs. therein.

[14] D.J. Hofman (for the PHOBOS Collaboration), Proc. XXXIX Rencontres de Moriond: QCD and High-Energy Hadronic Interactions (La Thuile, Italy, 2004), nucl-ex/0406026.

[15] R. Noucier (for the PHOBOS Collaboration), Proc. XXVII Int. Conf. on Ultra Relativistic Nucleus-Nucleus Collisions: Quark Matter 2004 (Oakland, USA, 2004), Eds. H.G. Ritter, X.-N. Wang, J. Phys. G **30** (2004) S1133.

[16] B.B. Back *et al.*, nucl-ex/0409021.

[17] L.D. Landau, Izv. Akad. Nauk: Ser. Fiz. **17** (1953) 51.

[18] E.L. Feinberg, Proc. Int. Conf. on Elementary Particle Physics (Smolenice, Czhechoslovakia, 1983), Ed. I. Lukáč, (Inst. of Phys. SAC, Bratislava, 1985), p. 81; Relativistic Heavy Ion Physics (Int. Rev. of Nuclear Physics, Vol. 6), Eds. L.P. Csernai, D.D. Strottman (World Scientific Pub. Co. Pte. Ltd., 1991), p. 341.

[19] P.A. Carruthers, LA-UR-81-2221, Proc. V Int. High Energy Heavy Ion Study Conf. (Berkeley, USA, 1981) ; P. Steinberg, Proc. XX Winter Workshop on Nuclear Dynamics (Trelawny Beach, Jamaica, 2004), nucl-ex/0405022.

[20] BRAHMS Collaboration, I.G. Bearden *et al.*, Phys. Rev. Lett. **94** (2005) 162301.

[21] J.D. Bjorken, Phys. Rev. D **27** (1983) 140.

[22] M. Basile *et al.*, Nuovo Cim. A **66** (1981) 129, **73** (1983) 329.

[23] For reviews, see: V.V. Anisovich, N.M. Kobrinsky, J. Nyiri, Yu.M. Shabelsky, Quark Model and High Energy Collisions (World Scientific, Singapore, 1985); J. Nyiri, Int. J. Mod. Phys. A **18** (2003) 2403.

[24] P.V. Chliapnikov, V.A. Uvarov, Phys. Lett. B **251** (1990) 192; for review, see W. Kittel, Proc. XLIV Cracow School of Theoretical Physics (Zakopane, Poland, 2004), Acta Phys. Pol. B **35** (2004) 2817.

[25] S. Eremin and S. Voloshin, Phys. Rev. C **67** (2003) 064905.

[26] PHOBOS Collaboration, B.B. Back *et al.*, Phys. Rev. Lett. **91** (2003) 052303.

[27] PHOBOS Collaboration, B.B. Back *et al.*, Phys. Rev. C **70** (2004) 021902.

[28] NA49 Collaboration, S.V. Afanasiev *et al.*, Phys. Rev. C **66** (2002) 054902.

[29] E895 Collaboration: J.L. Klay, Transverse mass and rapidity spectra of pions and protons from gold+gold collisions at the Alternating Gradient Synchrotron, PhD Thesis (U.C. Davis, 2001), see [2].

[30] UA5 Collaboration, G.J. Alner *et al.*, Phys. Rep. **154** (1987) 247.

[31] UA5 Collaboration, R.E. Ansorge *et al.*, Z. Phys. C **43** (1989) 357.

[32] W. Thomé *et al.*, Nucl. Phys. B **129** (1977) 365.

[33] V.V. Ammosov *et al.*, Phys. Lett. B **42** (1972) 519; C. Bromberg *et al.*, Phys. Rev. Lett. **31** (1974) 254.

[34] W.M. Morse *et al.*, Phys. Rev. D **15** (1974) 66.

[35] E. De Wolf, J.J. Dumont, F. Verbeure, Nucl. Phys. B **87** (1975) 325.

[36] OPAL Collaboration, G. Alexander *et al.*, Z. Phys. C **72** (1996) 191.

[37] ALEPH Collaboration, A. Heister *et al.*, Eur. Phys. J. C **35** (2004) 457; DELPHI Collaboration, P. Abreau *et al.*, Phys. Lett. B **372** (1996) 172; L3 Collaboration, P. Achard *et al.*, Phys. Rep. **399** (2004) 71.

[38] OPAL Collaboration, G. Abbiendi *et al.*, Eur. Phys. J. C **37** (2004) 25.

[39] DELPHI Collaboration, P. Abreau *et al.*, Z. Phys. C **70** (1996) 179.

[40] TASSO Collaboration, W. Braunschweig *et al.*, Z. Phys. C **45** (1989) 193.

[41] AMY Collaboration, H.W. Zheng *et al.*, Phys. Rev. D **42** (1990) 737.

[42] JADE Collaboration, W. Bartel *et al.*, Z. Phys. C **20** (1983) 187.

[43] LENA Collaboration, B. Niczyporuk *et al.*, Z. Phys. C **9** (1981) 1.

[44] MARK1 Collaboration, J.L. Siegrist *et al.*, Phys. Rev. D **26** (1982) 969.

[45] OPAL Collaboration, P.D. Acton *et al.*, Z. Phys. C **53** (1992) 539.

[46] Particle Data Group, S. Eidelman *et al.*, Phys. Lett. B **592** (2004) 1, and at `http://pdg.lbl.gov/` .

[47] `http://www.cern.ch/biebel/www/RPP04/` .

[48] I.M. Dremin, J.W. Gary, Phys. Lett. B **459** (1999) 341; A. Capella *et al.*, Phys. Rev. D **61** (2000) 074009; for review see I.M. Dremin, J.W. Gary, Phys. Rep. **349** (2001) 301.

[49] I.I. Roizen, E.L. Feinberg, O.D. Chernavskaya, Physics - Uspekhi **47** (2004) 427 [UFN, **174** (2004) 473]; J. Letessier, J. Rafelski, nucl-th/0504028.

[50] BRAHMS Collaboration, I.G. Bearden *et al.*, Phys. Rev. Lett. **88** (2002) 202301.

[51] STAR Collaboration, C. Adler *et al.*, Phys. Rev. Lett. **87** (2001) 112303.

[52] F. Ceretto (for the CERES/NA45 Collaboration, G. Agakichiev *et al.*), Proc. XIII Int. Conf. on Ultrarelativistic Nucleus-Nucleus Collisions: Quark Matter '97 (Tsukuba, Japan, 1997), Eds. T. Hatsuda *et al.*, Nucl. Phys. A **638** (1998) 467c; F. Ceretto, Charged hadron production in Pb-Au collisions at $158A$ GeV/c, Ph.D. Thesis (University of Heidelberg, 1998);

[53] F. Siklér (for the NA49 Collaboration, J. Bächler *et al.*.), Proc. XXIV Conf. on Ultrarelativistic Nucleus-Nucleus Collisions: Quark Matter '99 (Torino, Italy, 1999), Eds. L. Ricatti *et al.*, Nucl. Phys. A **661** (1999) 45c.

[54] NA50 Collaboration, M.C. Abreau *et al.*, Phys. Lett. B **530** (2002) 43.

[55] WA98 Collaboration, M.M. Aggarwal *et al.*, Eur. Phys. J. C **18** (2001) 651.

[56] E802 Collaboration, L. Ahle *et al.*, Phys. Rev. C **59** (1999) 2173; E917 Collaboration, B.B. Back *et al.*, Phys. Rev. Lett. **86** (2001) 1970.

[57] UA1 Collaboration, G. Arnison *et al.*, Phys. Lett. B **123** (1984) 108.

[58] P.K. Netrakanti, B. Mohanty, Phys. Rev. C **70** (2004) 027901; B. De, S. Bhattacharyya, Phys. Rev. C **71** (2005) 024903.

[59] J. Whitmore *et al.*, Phys. Rep. **10C** (1974) 273.

[60] D. Kharzeev, E. Levin, M. Nardi, Nucl. Phys. B **743** (2004) 329, erratum.

[61] D. Kharzeev, E. Levin, M. Nardi, Nucl. Phys. B **730** (2004) 448.

[62] A.M. Moraes, talk given at ATLAS Physics Week (CERN, Nov. 2004).

[63] For reviews see: P.M. Jacobs, X.-N. Wang, Prog. Part. Nucl. Phys. **54** (2005) 443; J. Ellis, Summary talk at Int. Conf. on High Energy Physics (Beijing, China, 2004), hep-ph/0409360; E. Levin, talk at Int. Workshop on Particle Multiplicity in Relativistic Heavy Ion Collisions: Focus on Multiplicity (Bari, Italy, 2004), hep-ph/0408039; D. Kharzeev, talk at XXXIX Les Rencontres de Moriond: QCD and Hadronic Interactions (La Thuile Italy, 2004), hep-ph/0408091; K. Tuchin, talk at XXXIV Int. Symposium on Multiparticle Dynamics (Sonoma County, California, USA, 2004), hep-ph/0410019; U.A. Wiedemann, Proc. XXVII Int. Conf. on Ultra Relativistic Nucleus-Nucleus Collisions: Quark Matter 2004 (Oakland, USA, 2004), Eds. H.G. Ritter, X.-N. Wang, J. Phys. G **30** (2004) S649.
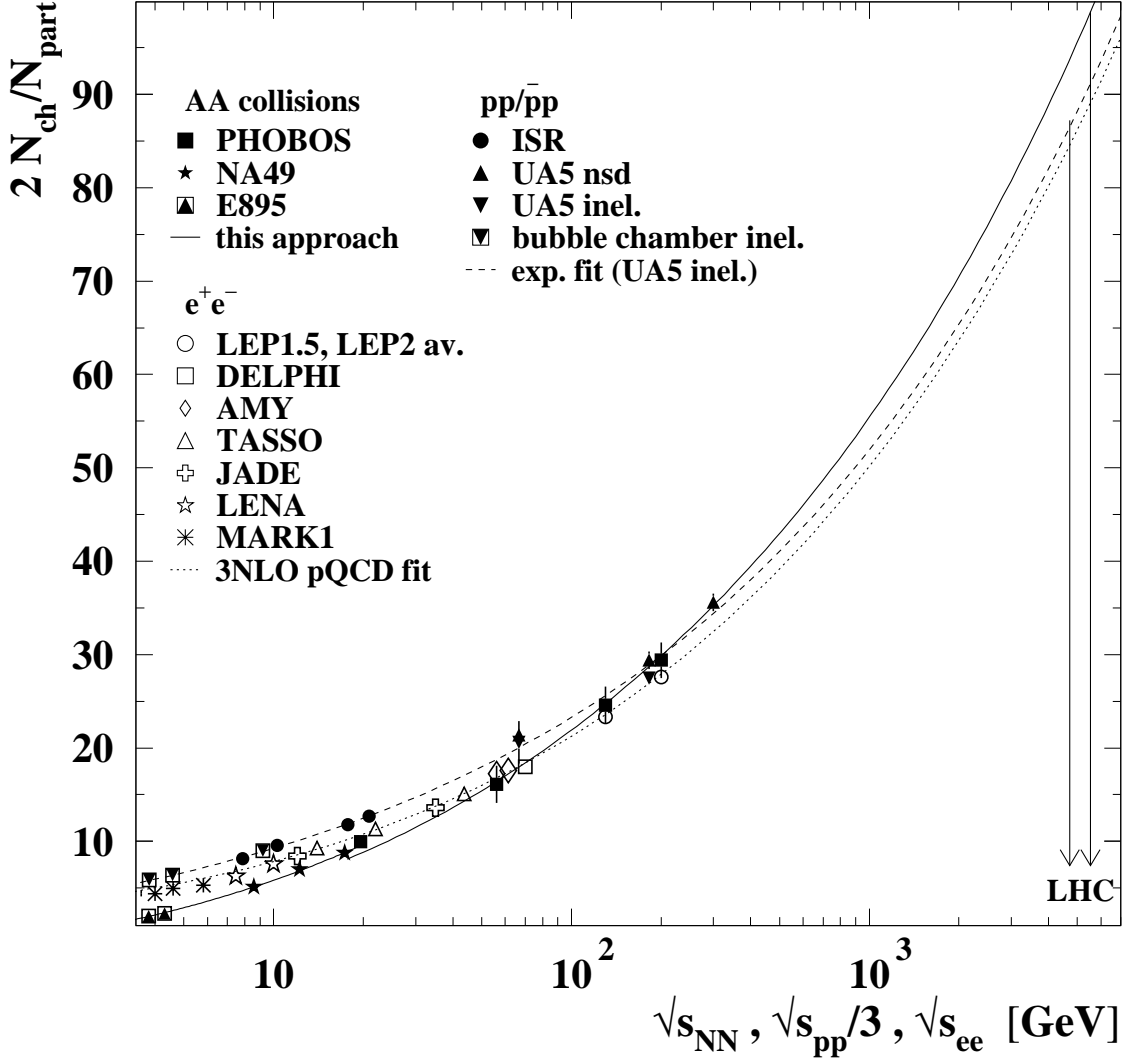
Figure 1: The charged particle mean multiplicity per participant pair as a function of the c.m. energy. The solid and combined symbols show the multiplicity value of the most central heavy-ion (AA) collisions at RHIC as measured by PHOBOS Collaboration (■) in [2,3,26,27], and by NA49 Collaboration at CERN SPS [28] (★) and by E895 Collaboration at AGS [29] (▣) (see also [2]), and, in p̄p collisions, the measurements made at CERN by UA5 Collaboration (▲ for non-single diffractive, ▼ for inelastic events) at $\sqrt{s_{\mathrm{pp}}} = 546$ GeV [30] and $\sqrt{s_{\mathrm{pp}}} = 200$ and 900 GeV [31] and, at lower c.m. energies, in pp collisions obtained at CERN-ISR (●) [32] and from bubble chamber experiments [33,34] (▼) , the latter compiled and analysed in [35]. (The inelastic UA5 data at $\sqrt{s_{\mathrm{pp}}} = 200$ GeV is extrapolated in [15] from the limited rapidity range to the full one.) The open symbols show the e^+e^- measurements: the high-energy LEP mean multiplicities averaged here from the recent data values (○) at LEP1.5 $\sqrt{s_{\mathrm{ee}}} = 130$ GeV in [36,37] and LEP2 $\sqrt{s_{\mathrm{ee}}} = 200$ GeV in [37,38], and the lower-energy data as measured by DELPHI [39] (□), TASSO [40] (△), AMY [41] (◇), JADE [42] (+), LENA [43] (★), and MARK1 [44] (✳) Collaborations. (See also [45,46,47] for data on e^+e^- and pp/p̄p collisions). The solid line shows the calculations from Eq. (2) based on our approach and using the corresponding fits (see text). The dashed and dotted lines show the fit to the pp/p̄p data from [30] and the 3NLO perturbative QCD fit [48] to e^+e^- data by ALEPH [37]. The arrows show the expectations for the LHC.
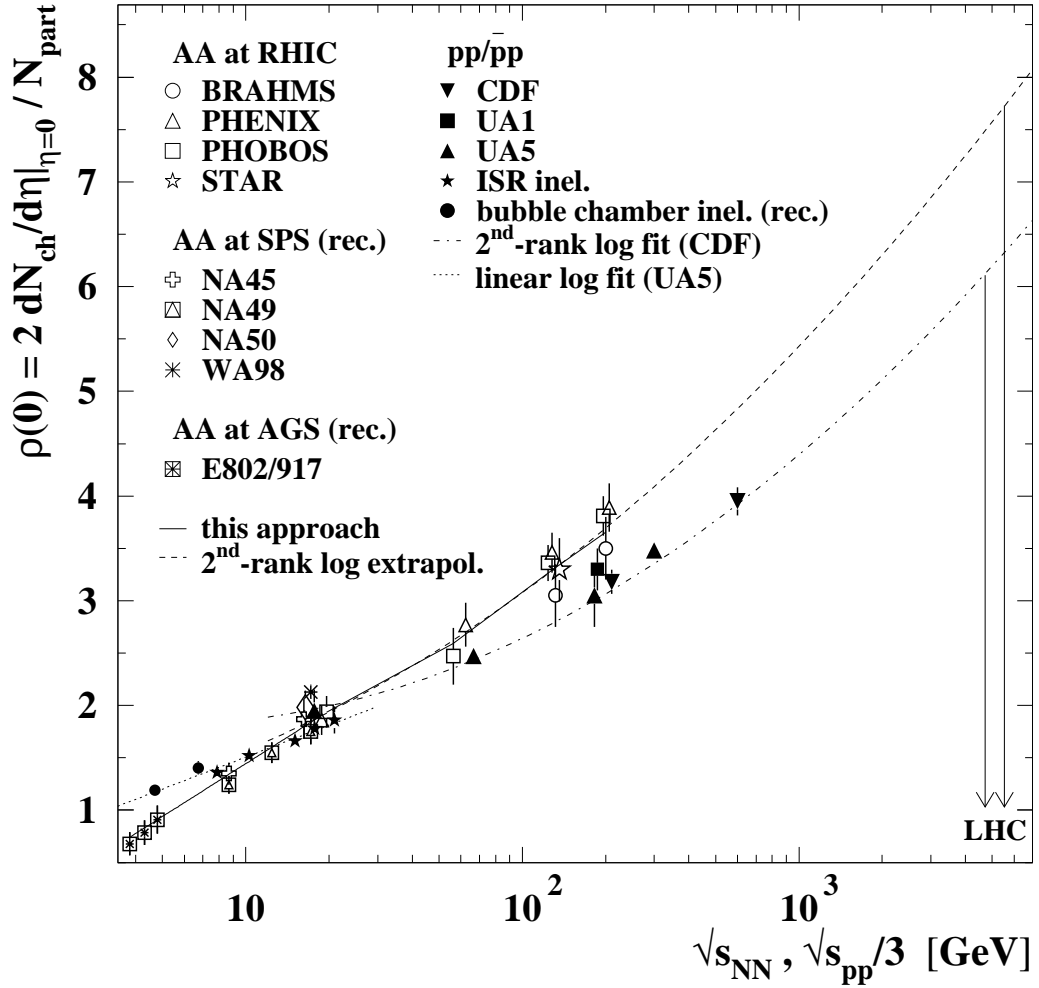
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Figure 2: Pseudorapidity density of charged particles per participant pair at midrapidity as a function of the c.m. energy of collision. The open and combined symbols show the pseudorapidity density values per participant pair *vs.* c.m. energy per nucleon, $\sqrt{s_{NN}}$, measured in the most central heavy-ion collisions at RHIC by BRAHMS [50] ($\circ$), PHENIX [10] ($\triangle$), PHOBOS [6,27] ($\square$), and STAR [51] ($\star$) Collaborations, and the density values recalculated in [10] from the measurements taken at CERN SPS by CERES/NA45 [52] (+), NA49 [53] ($\boxtimes$), NA50 [54] ($\diamond$) and WA98 [55] ($\ast$) Collaborations and at Fermilab AGS by E802 and E917 Collaborations [56] ($\boxtimes$). The nuclear data at $\sqrt{s_{NN}}$ around 20 GeV and the RHIC data at $\sqrt{s_{NN}} = 130$ GeV and 200 GeV are given spread horizontally for clarity. The PHENIX data at $\sqrt{s_{NN}} = 62.4$ GeV is taken from [11]. The solid symbols show the pseudorapidity density values *vs.* c.m. energy $\sqrt{s_{pp}}/3$ as measured in non-single diffractive $\bar{p}p$ collisions by UA1 [57] ($\blacksquare$) and UA5 [4,30] ($\blacktriangle$) Collaborations at CERN SPS, by UA5 at CERN ISR ($\sqrt{s_{pp}} = 53$ GeV), by CDF Collaboration at Fermilab [5] ($\blacktriangledown$), and in inelastic pp collisions from the ISR [32] ($\star$) and bubble chamber [34,59] ($\bullet$) experiments. The data from the bubble chamber experiments [34,59] are given as recalculated in [4]. The solid line connects the predictions from Eq. (2). The dashed line gives the fit to the calculations using the 2nd order log-polynomial fit function analogous to that used [5] in $\bar{p}p$ data. The fit function from [5] is shown by the dashed-dotted line. The dotted line shows the linear log approximation of UA5 to inelastic events [4]. The arrows show the expectations for the LHC. Note that e^+e^- data at $\sqrt{s_{ee}} = 14$ GeV to 200 GeV (not shown) follows the heavy-ion data [3].

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